EXPERIMENTAL STUDY OF THE BISTABLE FLOW IN TUBE BANKS OF TRIANGULAR ARRANGEMENT

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Abstract. *Banks of tubes are found in many applications in engineering, where cylindrical structures submitted to a transversely flowing fluid are present, as in heat exchangers, pipelines and transmission lines. By means of hot wire anemometry technique the presence of the bistability in in triangular tube arrays is investigated in an aerodynamic channel and the experimental results are interpreted by the flow visualization in a water channel. Results of side by side tubes and a row of tubes complement the study. Bistability occurs in flows over sets of bluff bodies forming a flip-flopping wake characterized by a biased flow switching at irregular intervals. This phenomenon can represent an additional source of dynamic instabilities. The aspect ratios p/d investigated were p/d=1.26 and p/d=1.6, where "p" is the pitch or the distance between the centers of adjacent cylinders and "d" the diameter. The experimental data were analyzed by statistical, spectral and wavelet tools. The time-frequency domain analysis of experimental signals by wavelets allows the detection of non permanent flow structures.*

Keywords*: turbulent flow, tube banks, hot wires, flow visualization, wavelets.*

1. INTRODUCTION

Tube banks are a very common configuration in engineering applications for the analysis of the phenomena that occur in various arrangement of circular cylinders nearly disposed, as found in heat exchangers, pipelines and transmission lines.

A very interesting phenomenon occurs when two circular cylinders placed side-by-size are submitted to a turbulent cross-flow. The flow that emanates through the gap between the cylinders is biased towards the rear surface of one of the cylinders, and has a narrow wake. This can be called as a flow mode. In the literature, bistability is the phenomenon where a floppy and random behavior of the gap flow changes intermittently the flow mode, from one cilinder to to other at irregular time intervals.

According to Zdravkovich and Stonebanks (2000) the leading feature of flow-induced vibration in tube banks is the randomness of dynamic responses of tubes, and even if the tubes are all of equal size, have the same dynamic characteristics, are arranged in regular equidistant rows and are subjected to an uniform steady flow, the dynamic response of tubes is non-uniform and random.

As the triangular geometry has a large utilization in many engineering applications, and as bistability has been found at two side-by-size cylinders classical geometry, and more recently at in tube banks with square arrangement, the triangular arrangement was chosen in this work. Besides, a need of new information about this phenomenon is necessary, due to the fact that the flow induced vibration and fluid–structure interaction are very dependent on the configuration or arrangement of the cylinders (side-by-side or tandem), which can be an additional excitation mechanism on the tubes.

Flow visualizations techniques are indispensable for the comprehension of the phenomena studied in laboratory conditions. Ziada (2006) presents a flow visualization study about vortex shedding, acoustic resonance and turbulence excitations in tube bundles in triangular arrangements of cylinders at various Reynolds numbers and pitch-to-diameter ratios. Alam *et al.* (2005) present a flow visualization study to the determination of flow configurations and fluid forces acting on two staggered circular cylinders of equal diameter in cross-flow. Olinto (2005) determined through experiments the presence of a biased and bistable flow mode of two cylinders placed in a side-by-side arrangement, and also presented flow visualization results of this configuration using a water channel.

Therefore, an experimental study applying hot wire technique complemented by a flow visualization analysis can lead to a better comprehension of the bistable flow phenomenon in tube banks.

2. THE BISTABLE EFECT

According Sumner *et al.* (1999), the flow over two side by side cylinders with different pitch-to-diameter ratios p/d can present wakes with different modes.

At intermediate pitch ratios (1.2<p/d<2.0) the flow is characterized by a wide near-wake behind one of the cylinders and a narrow near-wake behind the other, as shown schematically in Fig. 1a and Fig. 1b. This phenomenon generates two dominants vortex-shedding frequencies, each one associated with a wake: the narrow wake is associated with a higher frequency and the wide wake with a lower one.

Thereby, if the flow velocity is measured downstream the cylinders, for example along the tangent to their external generatrices, a switch mode can occur as shown in the scheme in Fig. 1c. According to previous studies, this pattern is independent of Reynolds number, and it is not associated to cylinders misalignment or external influences, what suggest an intrinsically flow feature.

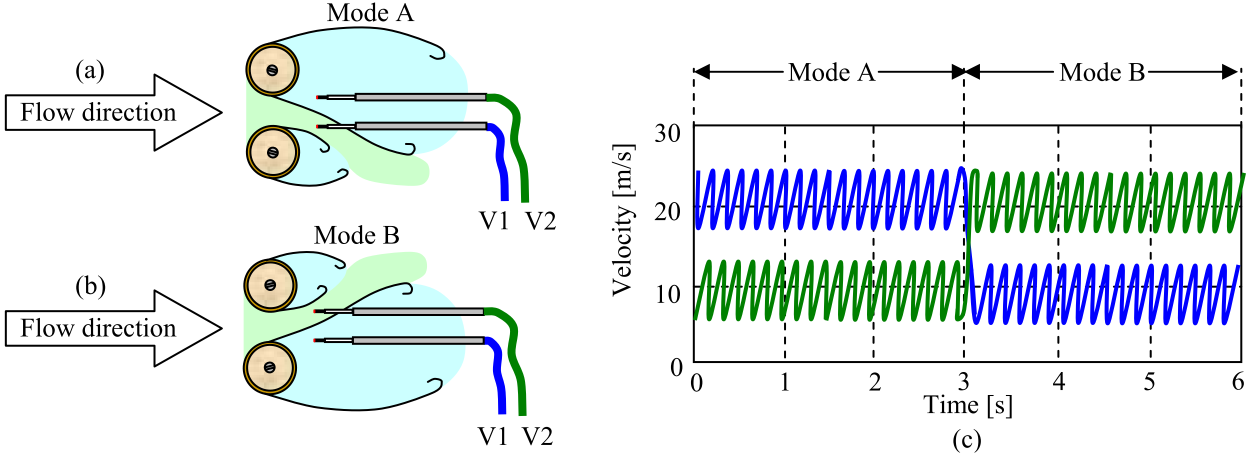

Figure 1. Bistability scheme for (a) mode A and (b) mode B, and the respective characteristical signals (c).

The transition between the asymmetric states, according to Kim and Durbim (1988), is completely random and it is not associated with a natural frequency. Through a dimensional analysis, they concluded that the mean time between the transitions is on order of about 10^3 times longer than vortex shedding period, and the mean time intervals between the switching process decreases with the increasing of Reynolds number. This is in accordance with Williamson (1985), who found for Re=300 a steady mean flow. As Strouhal numbers are relatively independent of the Reynolds numbers (Žukauskas, 1972), they concluded that there is no correlation between the bistable feature and the vortex shedding.

3. OBJECTIVES

The purpose of the present paper is to describe the biased and bistable flow mode in triangular tube arrays submitted to perpendicular flow. Results of side by side tubes and a row of tubes complement the study. The experimental results obtained with hot wire measurements in the aerodynamic channel are interpreted through flow visualization in a water channel. The aspect ratios chosen were p/d=1.26 and p/d=1.6.

4. THE EXPERIMENTAL TECHNIQUE

4.1 Aerodynamic channel

An acrylic aerodynamic channel (Fig. 2a) with a rectangular test section of 0.146 m height and width of 0.193 m was used to perform all the hot wire measurements. The air is impelled by a centrifugal 640 W blower, and passes through two honeycombs and two screens to reduce the turbulence intensity to about 1% in the test section. The reference velocity is measured by a Pitot tube, placed on one side wall of the aerodynamic channel, before the test section. Two hot wire probes (type DANTEC 55P11), with single wires perpendicular to the main flow, were used to measured velocity and velocity fluctuations with a DANTEC *StreamLine* constant temperature hot-wire anemometry system. The wires of both probes were maintained in horizontal position. A 16-bit data acquisition board (NATIONAL 9215-A) with USB interface was used to convert the analogical signal to digital series. The tubes had a diameter of 0.0321 m and were rigidly attached to the top wall of the test section in vertical position. The probe supports were also made of acrylic material, and fixed in both left and right walls, as shown in Fig. 2b. The mean error of the flow velocity determination with a hot wire was about 3%.

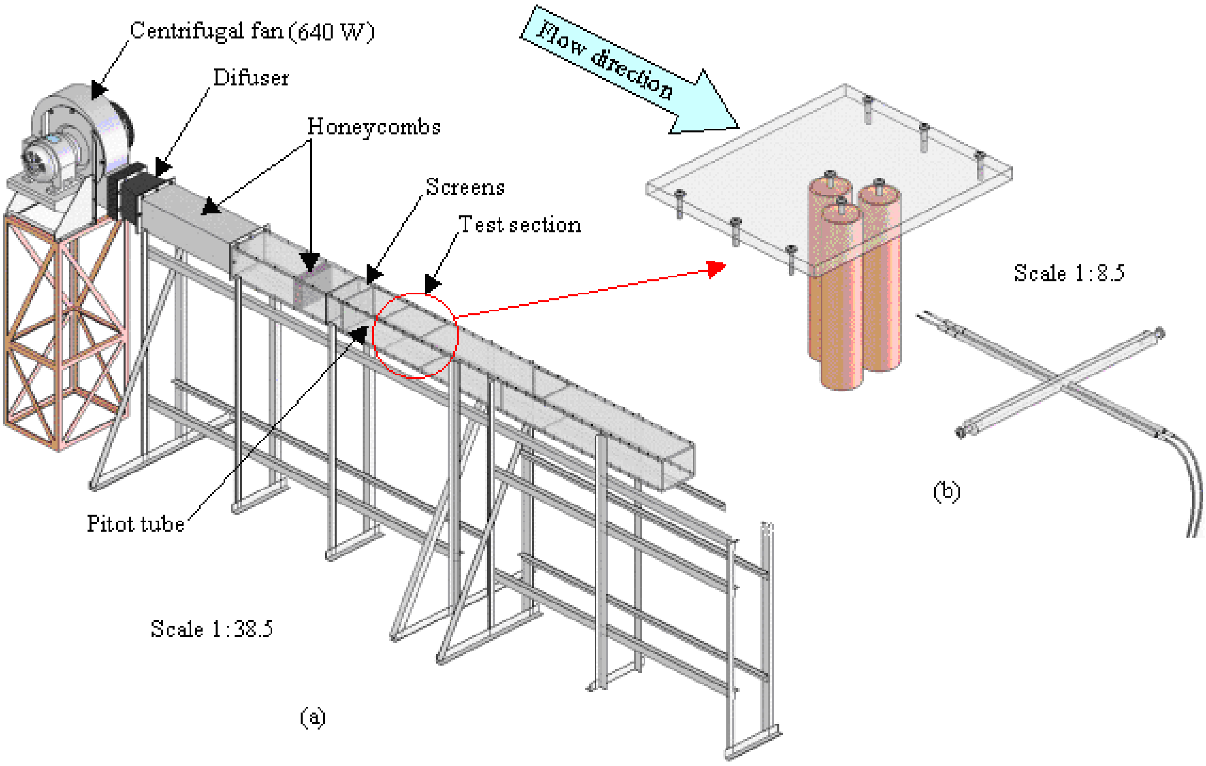

Figure 2. Schematic view of: (a) the aerodynamic channel and (b) test section.

4.1 Water channel

The closed circuit water channel (Fig. 3a) of the Hydraulic Research Institute of the Federal University of Rio Grande do Sul was used to perform the flow visualizations. The water channel has a settling chamber with a honeycomb which acts as a flow straightener, a nozzle, a 30 m long open channel (10 m upstream, 20 m downstream the test section) with 0.5×0.6 m rectangular cross section, a vertical gage to control water level, and a discharge tank with the return pipe to close the circuit. The maximum flow depth is 0.5 m which is controlled through the flow rate, by a set of valves in the feeding pipeline, and by the vertical gage placed in the discharge. The flow rate is read by an electromagnetic flowmeter and can vary from 0.0006 m³/s to 0.22 m³/s, resulting in velocities from 3×10^{-3} m/s to 1.1 m/s, with a water depth of 0.4 m in the test section.

A visualization test section (Fig. 3b), consist of two side walls, a base and a ceiling wall made of acrylic plates. The cylinders are rigidly attached to the base plate. The water level is maintained at 380 mm in the test section for all experiments. All the cylinders are built with commercial PVC tubes, with diameter of 0.06 m, and are covered by a very fine white PVC film. Inside each cylinder, there are six hoses, distributed in the following mode: 2 hoses at 0.06 m below the ceiling plate of acrylic, 2 hoses at the middle plane of the visualization section (at 0.15 m from the base or the ceiling plate) and 2 hoses at 0.06 m above the base plate of acrylic. Each one of the exits of these pairs of hoses has an inclination of 10° with the horizontal plane (one hose in relation to another). So, visualizations can be performed in these three planes, with different ink colors. In each line there is a special cylinder, with an inclined movable mirror to observe the behavior of the ink flow of the neighboring cylinder. The mirror can be moved up and down by a steel cable and a spring (Fig. 4a).

An ink distribution system was mounted to provide an adequate ink injection in the cylinders (Fig. 4b). It consists of three tanks, with red, green and blue ink (referent to the inferior plane, middle plane and top plane of visualization, respectively), each one with a volume about 0.002 m³, connected by PVC hoses to valves that control the ink flow through a complex ink distribution system under the base plate to the tubes and then to injection taps drilled on the tube walls. The base plate is covered by a thin white PVC film with purpose of enhancing the contrast of the ink traces and for lightning distribution. A Sony digital camera, placed above the bank, was used for taking picture shots (4.1Mp) or digital movies (VGA - 640×480 pixels, 30 frames per second). The results of the flow visualizations are presented through static pictures, obtained from the movies, where the flow direction is from the left to the right.

The velocities profiles were measured with a hot film probe (type DANTEC 55R42), in a vertical plane at 0.95 m upstream of the test section. Figure 4c shows the velocity profiles of for a 0.01 m³/s flow rate. Results show that the flow in the water channel presents a small velocity asymmetry.

Chow (1959) explains that this is the case for prismatic channels, where the flow is in fact three-dimensional, and in spiral usually due to small perturbations at the channel inlet.

(a) (b)

Figure 3. (a) Closed circuit water channel of Hydraulic Research Institute of Federal University of Rio Grande do Sul. (b) Visualization section mounted inside the test section.

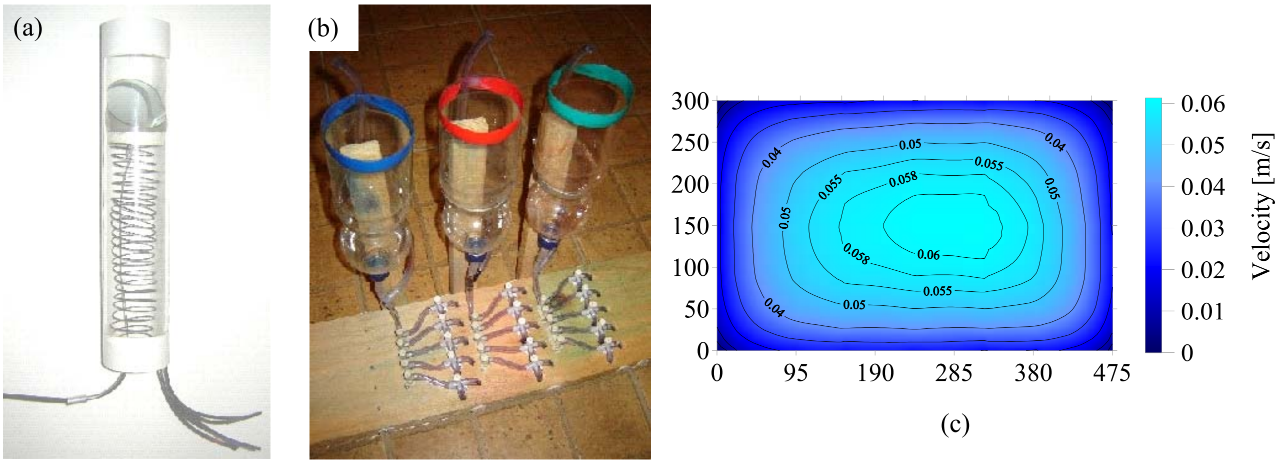

Figure 4. (a) Scheme of cylinder with an internal mirror. (b) Ink distribution system. (c) Velocity profiles of the visualization section for a flow rate of 0.01 m³/s.

5. MATHEMATICAL TOOLS

A time series can be analyzed by three ways: time domain, frequency domain and time-frequency domain.

The time domain analysis consists on the determination the four moments of the probability density function: mean (average), standard deviation, skewness and kurtosis. A frequency domain analysis can be done through the power spectral density function (PSD), which gives the energy distribution of the signal in time frequency domain (Bendat and Piersol, 1971). The time-frequency domain analysis can be made through wavelet transforms, discrete and continuous. A wavelet analysis is applied to time varying signals, where the stationary hypothesis cannot be maintained. The first one is used to make a multilevel decomposition of a time signal in several bandwidth values, accordingly with the selected decomposition level. The continuous wavelet transform is used to analyze the energy content of a signal through the so called spectrogram. In this work, Daubechies “db20” functions were used as bases of both discrete and continuous wavelet transforms. Indrusiak (2004) presents a more complete review of discrete and continuous wavelet transforms, applied to accelerating and decelerating turbulent flows. All mathematical analysis was made with Matlab ® software and its specific toolboxes for statistical, spectral and wavelet analysis.

6. RESULTS

The Reynolds numbers of the flow visualizations were calculated with the percolation velocity. This is the mean velocity of the tube bank in a top view, and depends on the reference velocity and the relation of the areas occupied by the cylinders (in a top view) and the whole tube bank area. Endres and Möller (2001) present a more complete study of the use of this parameter in tube-bank flow analysis.

6.1. A single cylinder

In order to verify reliability of the proposed flow visualization technique, flow visualization around a single circular cylinder, at various Reynolds numbers were performed. Figure 5 shows part of the results obtained, which were compared with the schematic regimes of vortex shedding characterized by Blevins (1990). From Fig. 5a is possible to identify a fixed pair of Föppl vortices in the wake, and from Fig. 5c a laminar vortex street is present. Some disturbances from the turbulence of the free stream can be observed.

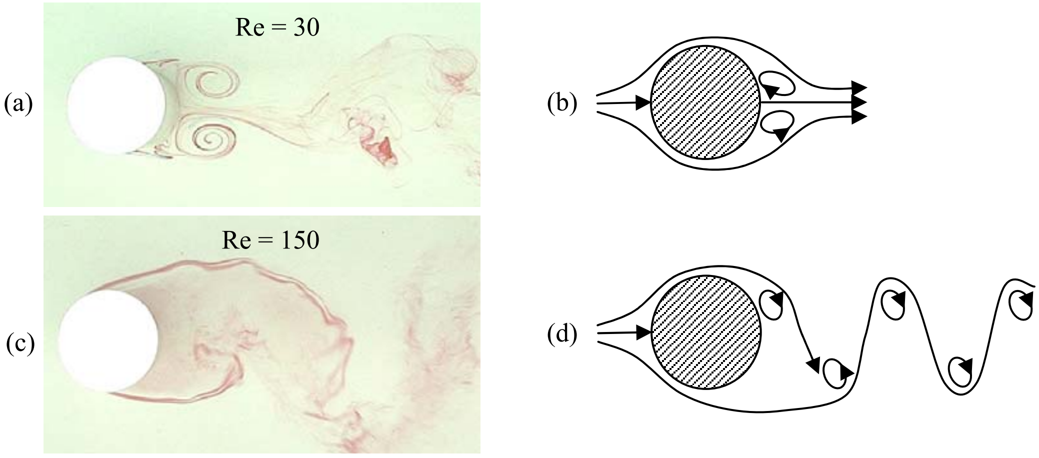

Figure 5. Flow visualization around a single circular cylinder, at Reynolds numbers (a) 30 and (c) 150, with their respective schematic regimes of vortex shedding (b) and (d) (Figs. (b) and (d) from Blevins (1990)).

6.2 Two side-by-side cylinders with p/d=1.26

Figure 6 shows the results for two side-by-side cylinders with p/d=1.26. The signals obtained from an 8 kHz acquisition frequency, at a distance of 0.03 m downstream the cylinders, show the presence of the bistable phenomenon (Fig. 6b and Fig. 6d). The results of this experiment agree perfectly with those found by Olinto (2005). The mode switches can be clearly observed through the wavelet decomposition shown in Fig. 6c and Fig. 6e, where the signals are reconstructed for frequency bands of 0-7.8125 Hz and of 0-3.9063 Hz, respectively. The Reynolds number for this experiment is Re = 2.8×10^4, relative to the tube diameter (32.1 mm) and the reference velocity of the air (at the entrance of the test section), 14.4 m/s. Figure 7 shows the results of the flow visualization for two cylinders side-by-side with p/d=1.26 and Re=7500.

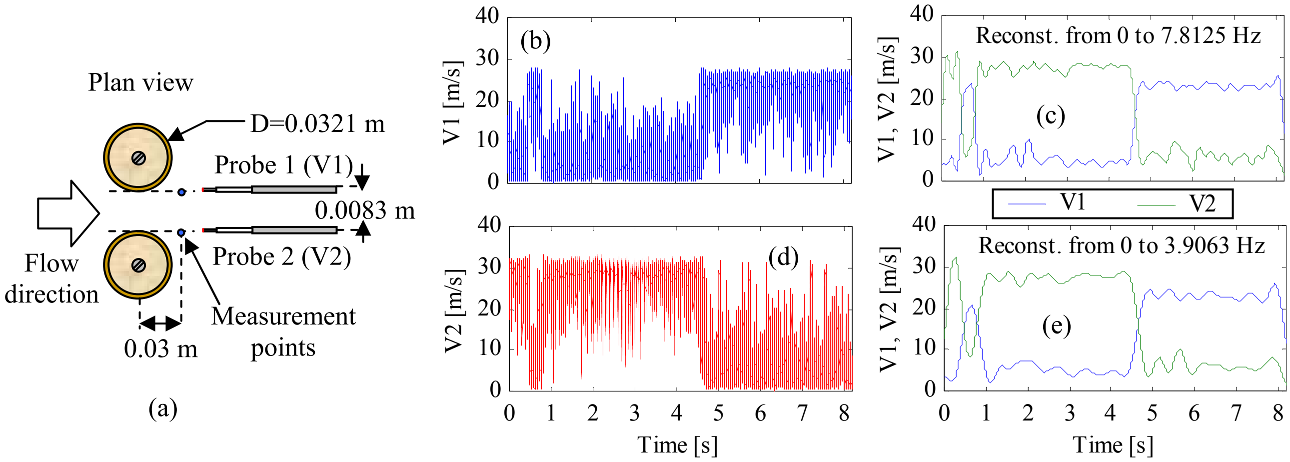

Figure 6. (a) Schematic view of the experiment and the probes positions. (b) and (d) are the velocity signals V1 and V2, respectively. (c) and (e) are the reconstructed signals using wavelet decomposition.

From Fig. 7a it is possible to see that a wide near-wake is formed downstream the left cylinder, and a narrow one downstream the right cylinder (Mode A). Figure 7b shows the Mode B, where this configuration has changed. The time elapsed between two modes is irregular and to capture this phenomenon the camera was set to acquire images for a period of time longer than 2 minutes. Similar results were found for the middle plane. Details show the view through the inclined mirrors, where the flow presents a predominant two-dimensional behavior.

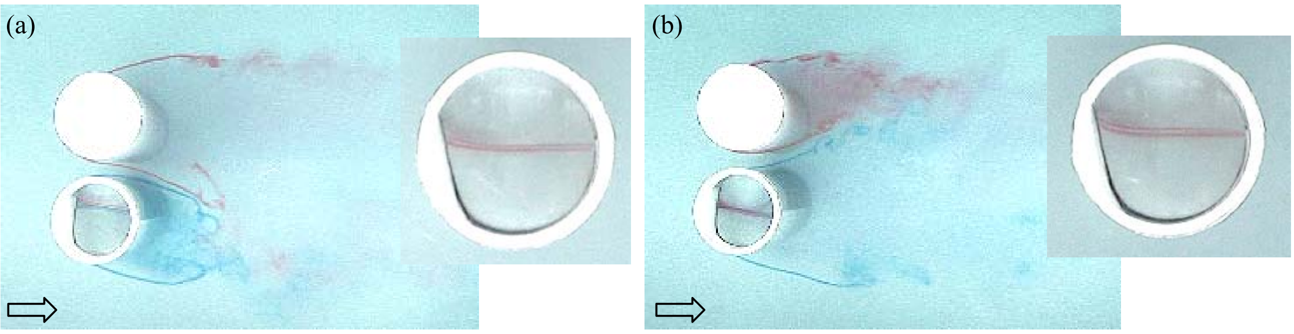

Figure 7. Flow visualization for two cylinders side-by-side with p/d=1.26 and Re=7500: (a) Mode A and (b) Mode B.

6.3 Three cylinders in delta configuration with p/d=1.6

Figure 8 shows the results for three cylinders in delta configuration with p/d=1.6. The signals obtained from a 25 kHz acquisition frequency at 0.007 m of distance, downstream the cylinders, show the presence of the bistable phenomenon (Fig. 8b and Fig. 8d). The mode switches can be clearly viewed through the wavelet decomposition shown in Fig. 8c and Fig. 8e, where the signals are reconstructed for frequency bands of 0-6.1035 Hz and of 0-3.0517 Hz, respectively. The Reynolds number for this experiment is Re = 3.2×10^4, with a reference velocity of 15.2 m/s.

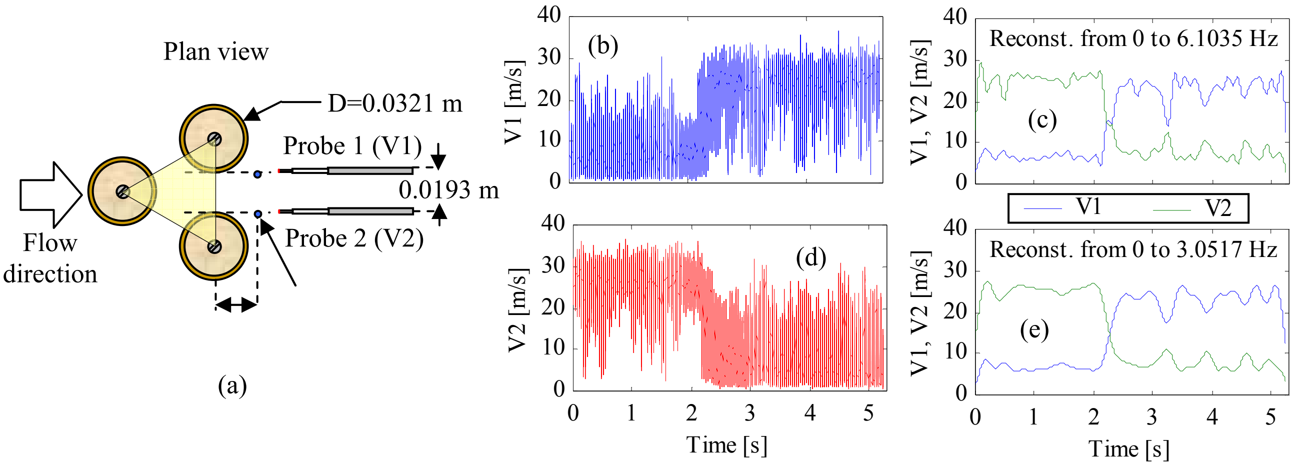

Figure 8. (a) Schematic view of the experiment and the probes positions. (b) and (d) are the velocity signals V1 and V2, respectively. (c) and (e) are the reconstructed signals using wavelet decomposition.

Figure 9 shows the power spectrum of the velocity signals, by means of continuous wavelet transforms (spectrograms) of these signals. The spectrogram in the Fig. 9a (relative to the signal V1) presents a low energy in the first part of the signal (0-2.25 s), distributed in the range of 20 to 150 Hz. This behavior is opposed to the obtained with the V2 signal, which spectrogram is shown in Figure 9b. The higher energy of V2 in this time interval is relative to the high velocity measured of the biased flow, and the lower energy of V1 is relative to the low velocity measured in the wide wake. After 2.25 s, this characteristic changes, and the spectrogram of V1 signal presents a higher energy while the spectrogram of V2 presents a low energy, also distributed in the range of 20 to 150 Hz.

Although, at about 2.25 s both signals present an increase in the energy values, indicating that the switching between two modes does not occur instantaneously, but it starts with an increase in the velocity fluctuations, for several frequencies, as observed by Alam *et al.* (2003). These authors concluded that between two flow modes there is an intermediary mode, with a different characteristic frequency from those in the narrow and wide wake. In order to study the flow modes, two segments of the velocities signals were separated to a statistical analysis (mode A and B, for the time series V1 and V2, respectively). Table 1 shows these results. The first mode (A) is composed by the values measured from 0.6 to 1.91 s, corresponding to a cluster with 32768 elements. The second mode (B) has 65536 elements, and the observed time interval is from 2.4 to 5.02 s. The switches between the velocity signals carry the statistical characteristics from each mode, and are associated to the switch in the gap flow direction.

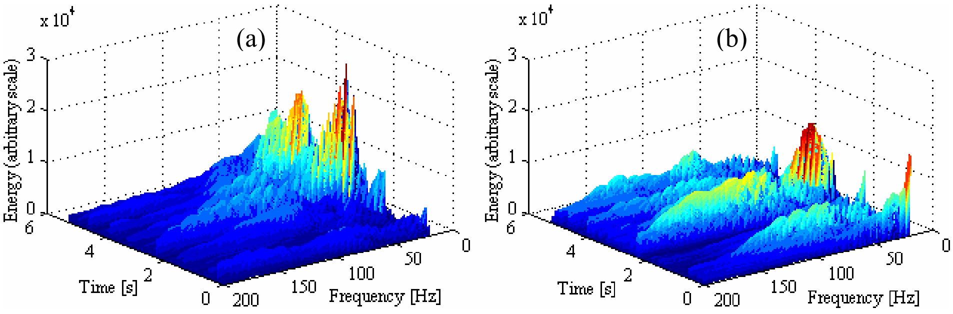

Figure 9. Continuous wavelet spectrum of the velocity signals of the figures 8b and 8d: (a) V1 and (b) V2.

Table 1. Statistical characteristics of the velocity series V1 and V2 of the figures 8b and 8d.

	Mode A		Mode B	
	V1	V2	V1	V2
Mean velocity [m/s]	6.47	25.58	23.28	7.66
Standard deviation [m/s]	3.45	2.87	4.59	4.6
Skewness	1.46	-1.63	-1.84	1.26
Kurtosis	7.22	10.11	6.79	4.71

Figure 10 shows the results of the flow visualization for three cylinders in delta configuration with p/d=1.6 and Re=7500, where the Mode A (Fig. 10a) and Mode B (Fig. 10d) are visible. Figure 10b and 10c show a predominant two-dimensional flow behavior through the inclined mirrors for Mode A and B, respectively.

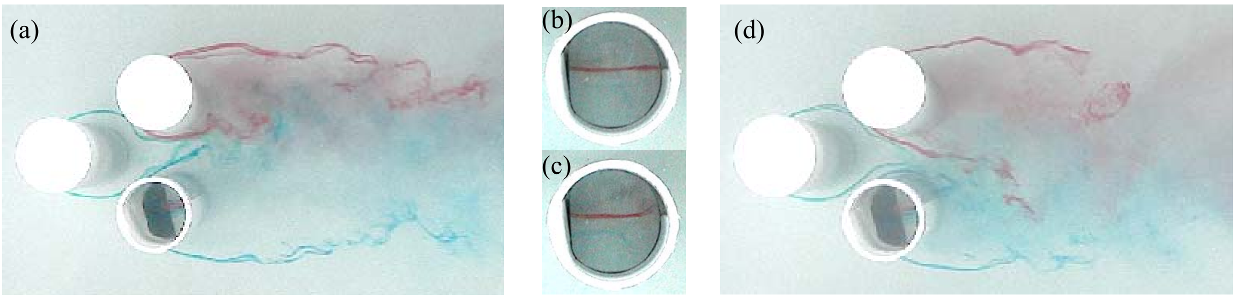

Figure 10. Flow visualization for three cylinders in delta configuration, p/d=1.6 and Re=7500: (a) Mode A and (d) Mode B. Details of the inclined mirrors: (b) Mode A and (c) Mode B.

6.4. Single row of cylinders

Figure 11 shows the results of the flow visualization for one single row of cylinders, at Reynolds number 7500 for p/d=1.26 and p/d=1.6, respectively. The pattern found for both cases is illustrated in Fig. 11c, and agreed with one of the regimes found by Zdravkovich (1997) and Olinto (2005).

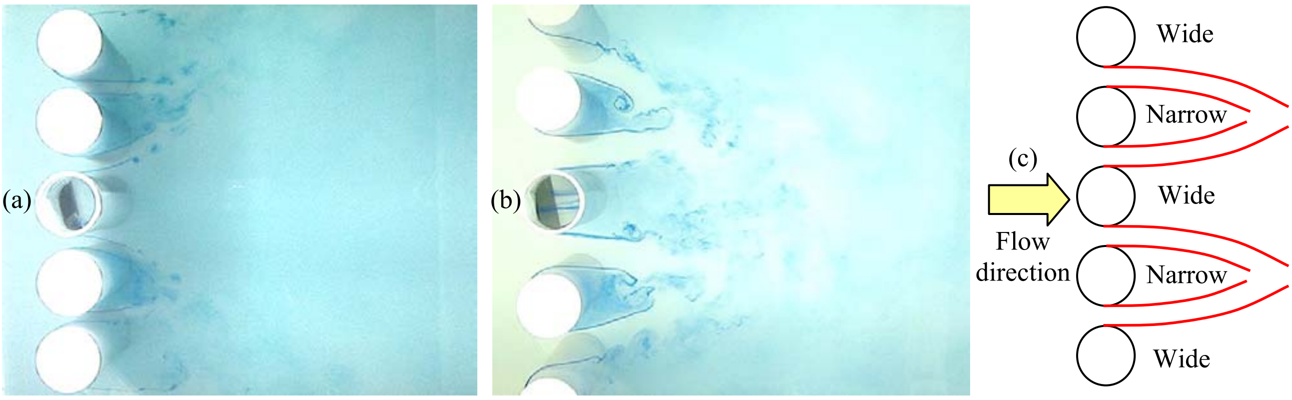

Figure 11. Flow visualization for one row of cylinders at Re=7500: (a) p/d=1.26 and (b) p/d=1.6, and the identified flow pattern (c), where the term ”Wide” means “Wide near-wake” and “Narrow” means “Narrow near-wake”.

This stable wake pattern is verified, where the cylinder of the center presents a wide wake, and their neighbors a narrow one. The flow mode does not change with time. Between consecutive visualizations, this pattern can be different, where the wide wake is verified behind another cylinder. This happens for both aspect ratios, but, the flow is never bistable for one row of cylinders.

7. CONCLUSIONS

This paper presents the experimental study of the bistable flow on two tubes placed side by side, three tubes in triangular arrangement and tubes forming a single row. The pitch to diameter in all configurations were p/d=1.26 and p/d=1.6. An aerodynamic and a water channel were used. Hot wire anemometry technique was used to measure the velocity and velocity fluctuations of the air flow in the aerodynamic channel. Flow visualization was performed in a water channel.

According to many authors, the bistability effect was detected in the experimental measurements for two side-by-side cylinders. This effect was also found for the delta triangular arrangement for three cylinders (when one cylinder is upstream and two downstream).

The flow visualizations results show that the bistable effect is clearly visible for two side-by-side cylinders at both pitch ratios p/d=1.26 and p/d=1.6. For one row of cylinders a stable wake pattern is verified, but, between consecutive experiments this pattern varies between different modes.

By increasing the numbers of rows in a bank, a more accurate analysis is necessary to confirm the presence of this phenomenon in triangular arrays as found by Olinto (2005) in square arrays. In this case, the presence of the bistability could result in an additional excitation mechanism on the tubes.

Future hot wire measurements and flow visualizations analysis are intended to characterize a five rows tube bank, with triangular arrangements, for the aspect ratios of p/d=1.26 and p/d=1.6. The combination of hot wire measurement and flow visualization can be helpful for better elucidating the presence of bistable flow phenomenon in triangular cylinder arrangements

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